Search for long GWs using HEN triggers

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Outline

1. Gamma Ray Bursts
2. Long GWs
3. Detection strategies and search algorithm
4. Conclusions

Gamma Ray Bursts (GRBs)

- GRBs are considered the most energetic phenomena in the recent Universe.
    - Distribution extends to cosmological distances.
- They are broadly classified into two categories i) Long and ii) short GRBs and mainly arise from
    - Collapse of massive stars and
    - Merger of BNS
- Even though they are copious emitters of photons, they are also expected to emit[1],
    - High Energy Neutrinos (HENs) of $\sim 10^{11} eV - 10^{16} eV$
    - Gravitational waves (GWs)

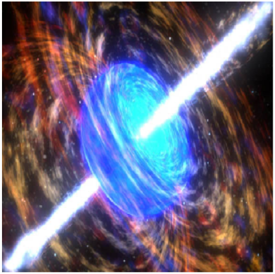


Image Credit: NASA

[1] P Mészáros, *Rep. Prog. Phys.* **69** *2259 (2006).*

Photons, HENs and GWs

- A relatively popular, fireball model of GRBs predict both photons and HENs originating inside the jet.
- Photons
    - Synchrotron by electron ($\geq$ 100 MeV)
    - Inverse Compton and $p\gamma \rightarrow \pi^0 \rightarrow \gamma\gamma$ (GeV and TeV)
- HENs
    - The dominant process is $p\gamma \rightarrow \pi^+ \rightarrow \nu_\mu e^+ \nu_e \bar{\nu_\mu}$ (TeV, PeV, EeV)
    - Neutrinos carry $\sim 5\%$ of the energy of the proton.
- GWs
    - Various instabilities in the progenitor and the accretion disc around it.

Search for GWs and HENs

- The past decade has seen the advent of new detectors that look for GWs and HENs from astrophysical sources like GRBs.
  - GW detectors - LIGO, VIRGO, GEO etc.,
  - Neutrino detectors - IceCube, ANTARES
- Till now there has been no direct detection of GWs or HENs from GRBs.
  - Upper limit constraints on the GW[2] and HEN emission from GRBs [3].
- Even though the individual detectors haven't seen anything yet, coincidence analyses offer better prospects for such a detection.
- In this talk I describe the search for long duration GWs in LIGO-VIRGO data in coincidence with HEN candidates from IceCube.
  - Choked GRBs and low luminous GRBs

[2] LIGO Collaboration, *ApJ* **681** *1419 (2008).* [3] IceCube collaboration, *Nature* **484**, *351354.*

Models of long GWs

- Accretion disc instabilities (ADI)[4,5]
  - Accretion disc or torus surrounding the inner core in CCSNe or central engine in Collapsar can fragment into clumps.
  - Depending on the mass of central core and the dynamics connecting the core and disc, the clump can be as big as $\sim M_\odot$.
  - GW strain $h \sim 10^{-23} \left(\frac{f}{1000Hz}\right)^{2/3}$ for a source at a distance of 100 Mpc; duration of $\sim$ 100 secs.

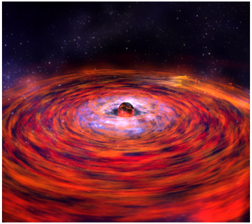


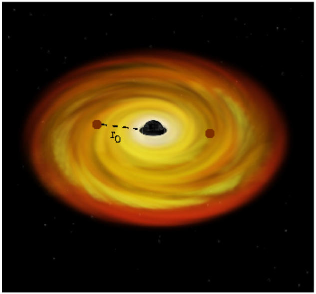
Image Credit: NASA

[4] Piro and Pfahl, *APJ* **658**, *1173 (2007).*

[5] Putten, *APJ Lett.* **575**, *71 (2002).*

Simple ADI model[6]

INITIAL



credit: NASA/CXC/M.Weiss

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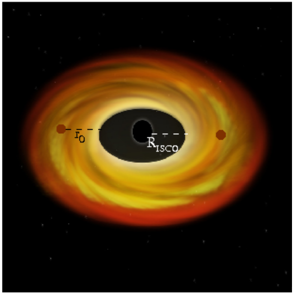


credit: NASA/CXC/M.Weiss

- $f_{GW} = \frac{1}{\pi}\sqrt{\frac{G\ M_{BH}}{(r_0 + R_{ISCO})^3}}$
- $r_0 \sim 100km$ (const) and $R_{ISCO} = f(J_{BH}, M_{BH})$
- Formation of clumps requires larger disc or outer envelope.

[6] C Ott and L Santamaria, *LIGO document T1100093 (2011)*.

Detection strategy

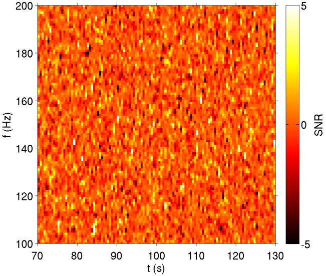
- Select HEN triggers from the periods when both IceCube and LIGO detectors were on.
    - IceCube's 22-string run overlaps with last six months of LIGO's S5 run ($\sim$ May 2007 - Oct 2007).
- Select a time window around each of those triggers to look for GW signal in LIGO data consistent with the HEN direction.
    - Time window of 1500 sec (-600 sec to +900 sec around the trigger); accounts for various GW production mechanisms[7,8].
    - 100-1200 Hz band in LIGO data (most sensitive band).
    - Since angular errors of the IceCube triggers ($\sim 3^o$) are larger than that of the GW search ($\sim 1^o$), grid the sky patch of each trigger and pick the hottest grid point in the GW search.

[7] Baret et. al.,, *Astropart. Phys.* **35**, *1 (2011).*

[8] A Corsi and P Mészáros, **702**, *1171 (2009).*

GW search algorithm

- Cross-correlation based GW analysis, involving two LIGO GW detectors.
- Frequency-time (ft)-maps are produced using the cross-correlated data from the two detectors.
- Look for clusters of bright pixels in the ft-map using clustering algorithms.
    - GW signals will show up as clusters of high SNR pixels in the map.
    - Have to take care non-stationarity and glitches in the data[9].
- For sensitivity studies and upper limit calculations, use simplified model of ADI waveforms



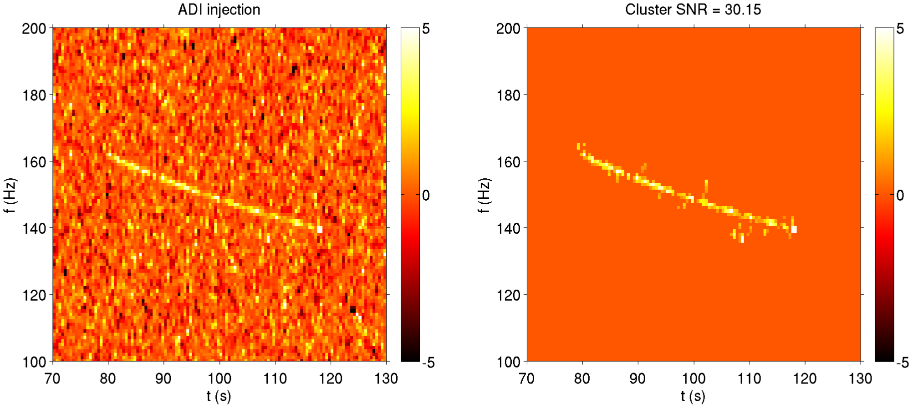
[9] T Prestegard et. al., *Class. Quantum Grav.* **29** *095018 (2012).*

Detection statistics

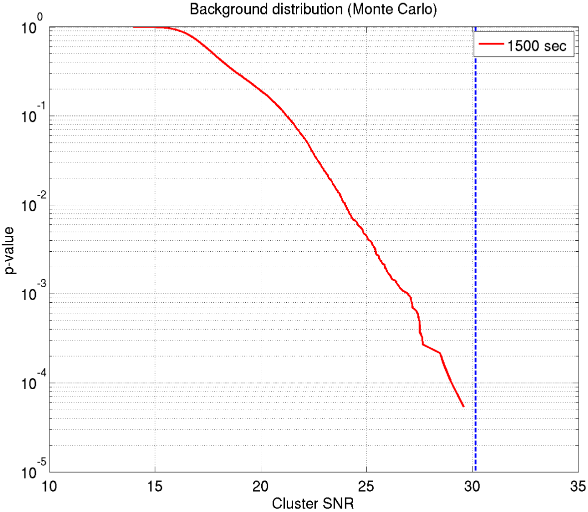
- A complete description of the method and quantitative details of the GW pipeline is already published[10].
- Estimators for GW power $\hat{Y}$ and its variance $\hat{\sigma}_Y^2$ are given by
    - $\hat{Y}(t;f) = 2\mathrm{Re}[\tilde{Q}_{IJ}(t;f) s_I^*(t;f) s_J(t;f)]$ where $s_I(t) = n_I(t) + h_I(t)$.
    - $\hat{\sigma}_Y^2 = \frac{1}{2}|\tilde{Q}_{IJ}(t;f)|^2 P_I(t;f) P_J(t;f)$ where $P_I(f) = 2|s_I|^2$
- filter function $\tilde{Q}(t;f) = \frac{e^{2\pi i f \Omega \cdot \Delta x_{IJ}/c}}{\sum_A F_I^A(t;f) F_J^A(t;f)}$
    - $\hat{\Omega}$ is the direction of the source
    - Δx_{IJ} is the distance vector connecting the two interferometers I and J
    - F^A's are the response functions of interferometers for GW polarization A; we sum over + and × polarizations.
- For multiple pixels, combine $\hat{Y}$'s with $\hat{\sigma}^{-2}$ as weights.

[10] E. Thrane et. al., *Phys. Rev. D* **83**, *083004 (2011).*

An example injection and recovery (ADI at 10 Mpc)



Background distribution



Conclusions

- GRBs are considered one of the strongest candidates for first detection of GW signal.
- Coincidence analyses of GWs with HEN and EM triggers offer better prospects for the detection of GWs from GRBs using current and next generation of interferometric GW detectors.
    - With HEN triggers, we can look for GRBs which are optically faint or dark, like low luminous and choked GRBs.
- From the sensitivity studies using simple ADI waveforms, we find that the current planned search for long GWs can potentially reach up to $\sim 10 - 100$ Mpc for optimistic models.
    - This is within the range of nearby GRBs observed electromagnetically.
    - Potentially there may be more that lack EM observations.